NACA

RESEARCH MEMORANDUM

REDUCTION OF WAVE DRAG OF WING-BODY COMBINATIONS AT

SUPERSONIC SPEEDS THROUGH BODY DISTORTIONS

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NATIONAL ADVISORY COMMITTEE
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The word "interference" is usually associated with adverse effects. However, interference between the components of an airplane or missile can also be beneficial. The methods of drag reduction by body distortion are examples. Figure 1 shows a simplified picture of the mechanics of this beneficial interference. A wing with a biconvex section is mounted on a cylindrical body. The dashed curve represents a body distortion which produces a drag-reducing interference. This distortion creates a negative pressure region to relieve the compression of the air on the forward part of the wing, and it creates a positive pressure region to compensate for the expansion of the air flowing over the after part of the wing. The problem to be solved by all the drag-minimization theories is to determine the magnitude and shape of this distortion that will reduce the wave drag on the wing as much as possible without unduly increasing the body drag.

There are several methods for doing this. The original method is the transonic area rule, which is limited to Mach numbers near unity. The so-called supersonic area rule is limited to slender configurations. Separate linear-theory investigations have been made by Lomax and Heaslet (ref. 1) and by Nielsen (ref. 2) to study the problem of drag minimization outside the region of applicability of these rules. This paper will discuss the theoretical bases of the theories of references 1 and 2 and present experimental results. A method recently investigated at the Langley Aeronautical Laboratory will also be discussed.

In reference 1 the problem of drag minimization is solved without recourse to body boundary conditions. Rather than treating actual shapes, the theory deals with multipole distributions along the body axis to find the minimum condition. Then the body shape is found from the resulting multipole distribution as the last step. The resulting body contains two types of distortion. One type is the axisymmetric distortion due to the sources. The other type is the nonaxisymmetric distortion due to higher order multipoles. Figure 2 shows the experimental verification of the ability of these distortions to produce drag reductions. The theory was applied to a wing of elliptic plan form for a design Mach number of $\sqrt{2}$. The body contained both axisymmetric and nonaxisymmetric distortions. Transition was fixed to minimize change in viscous effects. The quantity ΔC_D is the drag with the distorted body minus the drag with the

undistorted body, so that negative values represent drag reductions. The
theoretical drag reduction at the design Mach number is shown. A signif-
icant portion of this reduction is also realized experimentally over the
Mach number range of 1.1 to 1.4.

In reference 2 a different approach to the problem of determining
the body distortions is used. The basic difference is that in reference 1
multipoles are distributed along the body axis, whereas in reference 2 the
boundary conditions on the wing and body surfaces are satisfied by using
the quasi-cylindrical theory of reference 3. The body shape is obtained
by minimizing the expression for the drag of the entire combination by
the standard method of the calculus of variation. The shape of the body
distortions is the minimizing variable. Both axisymmetric and nonaxisym-
metric distortions are obtained. The quasi-cylindrical restriction in
this theory adds flexibility in that it makes possible direct computation
of the drag reduction to be expected from the optimized configuration if
it is operated at off-design conditions.

In figure 3, the model to which this theory was applied is shown.
The design Mach number is $\sqrt{2}$. The wing leading edge is sonic. This model
and models with wings of two other aspect ratios were tested to determine
the sensitivity of the theory to aspect ratio. Several bodies were tested
to determine the effect of the two types of distortion. Body B_1 is an
undistorted cylindrical body with a conical nose, and B_2 contains the
axisymmetric distortion. It is this distortion that removes volume from
the body. The other distortions rearrange the volume without removing
any. Bodies B_3 and B_4 contain both the distortion of B_2 and non-
axisymmetric distortions. Body B_4 is a modification of the optimized
body B_3. The dashed curves in the upper sketch show the plan-form sec-
tion of B_4.

The ability of each of these body distortions to produce a drag
reduction at the design Mach number is shown in figure 4. Transition
was fixed on all models to minimize change in viscous effects. The drag
reduction due to the axisymmetric distortion is shown in the upper left
of the figure. This is obtained by subtracting the drag of the model
with the undistorted body B_1 from the drag with the body B_2. Simi-
larly, the drag reductions due to the nonaxisymmetric distortions are
obtained by subtracting the drag with the distorted body B_2 from the
drags with bodies B_3 and B_4. These results are shown in the upper
right and lower left parts of figure 4. The fourth part of the figure
shows the total effect of both types of distortion by comparing bodies
B_4 and B_1. As before, negative values of ΔC_D indicate drag reduc-
tion. The axisymmetric distortion provides a significant drag reduction
for all aspect ratios although not to the extent predicted by theory.

This difference between theory and experiment is due to the fact that linear theory predicts too large a value for the wave drag of a wing with sonic leading edge. This means that the body shapes obtained are not the best possible for reducing the drag. If a better wing-alone theory were available for wings with sonic leading edge, a body shape that would give greater experimental drag reduction could be obtained. In the upper right of figure 4, theory predicts a large drag reduction for the nonaxisymmetric distortion of B_3. Actually the drag is increased. Liquid-film pictures showed that this increase is not due to flow separation. Instead it is a result of the large indentation in body B_3 which violates the quasi-cylindrical restriction of the theory. If this body is made more quasi-cylindrical by arbitrarily reducing the nonaxisymmetric distortion by one-half to obtain B_4, drag reduction in addition to that due to the axisymmetric distortion is obtained - as shown in the lower left part of the figure. The last part of figure 4 shows that the total effect of both types of distortion ($B_4 - B_1$) is to provide about 35 counts of drag reduction for all aspect ratios.

Figure 5 shows the effect of Mach number on drag reduction. As in figure 4, the quantity ΔC_D is compared for each of the distortions. The upper left part of the figure shows the effect of the axisymmetric distortion of B_2. The upper right part is for the nonaxisymmetric distortion of B_4. The lower part is for the combined effect of these two distortions. This figure supports the statement made for figure 4 that the difference between theory and experiment is due to the sonic leading edge of the wing. As the Mach number is increased from the value at which the leading edge is sonic ($M = \sqrt{2}$), theory and experiment come into good agreement. Figure 5 also shows that the nonaxisymmetric distortion is the most effective for maintaining drag reduction at other than the design Mach number. The axisymmetric distortion slightly increases the drag at $M = 1.75$. At this same Mach number the nonaxisymmetric distortion still provides about 10 counts of drag reduction. The loss of drag reduction as the Mach number is changed from its design value is primarily due to the movement of the Mach wave across the wing surface. The importance of this effect increases as the aspect ratio increases. This means that the Mach number range over which drag reduction is maintained will increase as the aspect ratio is decreased. For example, theory shows that the wing with aspect ratio of 1.33 maintains a drag reduction up to $M = 1.95$, compared with $M = 1.8$ for the wing with aspect ratio of 2.66.

The question arises as to how the supersonic area rule compares with these linear theories when applied to nonslender configurations. In order to compare the body shapes, the area rule and the quasi-cylindrical theory were applied to a wing with sonic leading edge and an aspect ratio of 1.33. The results are shown in figure 6. As might be expected, the body shapes differ considerably.

Another method of altering the body cross-sectional shape of swept-wing—body combinations to obtain further reductions in wave drag has been investigated recently at the Langley Aeronautical Laboratory. This method involves contouring the fuselage side to conform approximately to the streamline paths that would exist over the swept wing if it were of infinite span while preserving a satisfactory area development for the entire configuration.

The configuration investigated is shown in figure 7. The wing had an aspect ratio of 4.0, a taper ratio of 0.6, and a quarter-chord-line sweep of 45°. The solid lines indicate the body contour obtained through an axisymmetrical application of the transonic-area-rule principle. The dashed lines indicate the wing-body juncture of the second configuration, which was made to conform to the calculated streamline shape. This streamline shape was calculated with the use of experimental two-dimensional velocity distributions. These data were measured at a Mach number corresponding to the velocity component normal to the swept-wing leading edge. The body cross section was then adjusted at the top and bottom so that the longitudinal area development was identical with that of the axisymmetric area-rule configuration. The fairing behind the wing trailing edge was arbitrary.

Tests of the two configurations were made in the Langley transonic blowdown tunnel at a Reynolds number of about 2.5 × 10^6 based on the wing mean aerodynamic chord and at angles of attack up to about 10°. Transition was fixed to minimize change in viscous effects.

Some of the results of the investigation are presented in figure 8. Plotted are drag coefficients based on total wing area as a function of Mach number for two lift coefficients, 0 and 0.4. The solid lines refer to the axisymmetric area-rule indentation, and the dashed lines refer to the distorted indentation. As indicated, significant reductions in drag were obtained by contouring the wing-fuselage juncture to conform approximately to the calculated streamline shape. These gains were maintained through a large range of lift coefficient as indicated by the data at a lift coefficient of 0.4.

In summary, the methods discussed provide sizable reductions in drag for aspect ratios of current interest. These drag savings are maintained over a wide Mach number range, particularly for low-aspect-ratio wings. At the design Mach number, a significant part of the drag reduction is due to the nonaxisymmetric distortion. At other than the design Mach number, most or all of the drag reduction is due to the nonaxisymmetric distortion.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., Feb. 10, 1956

REFERENCES

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LINEAR-THEORY CONCEPTS OF DRAG MINIMIZATION

NEGATIVE PRESSURE
REGION

POSITIVE PRESSURE
REGION
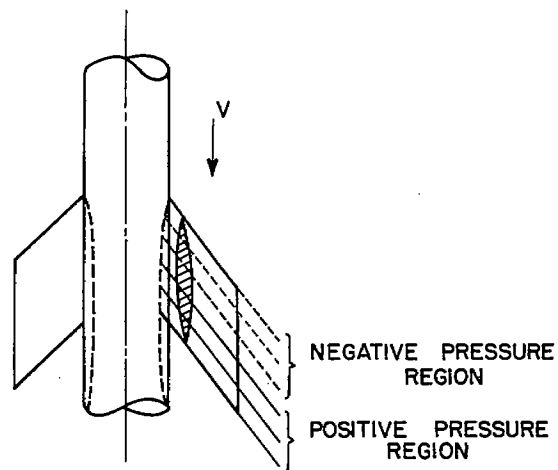
Figure 1

DRAG SAVING BY LOMAX METHOD

DESIGN MACH NUMBER = $\sqrt{2}$

DISTORTED
BODY
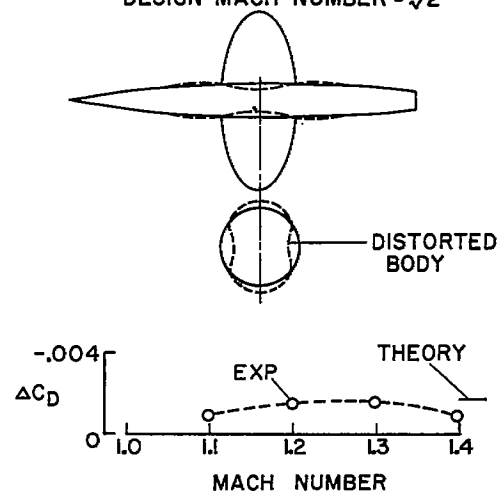
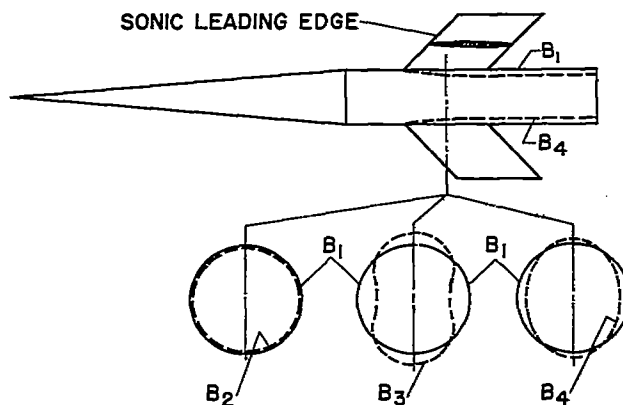Figure 2

MODELS DESIGNED BY NIELSEN METHOD
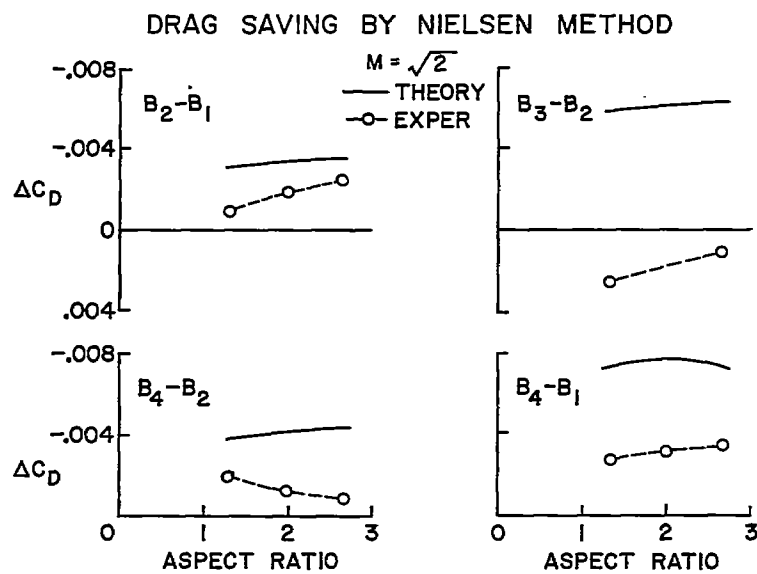$M = \sqrt{2}$

Figure 3

DRAG SAVING BY NIELSEN METHOD
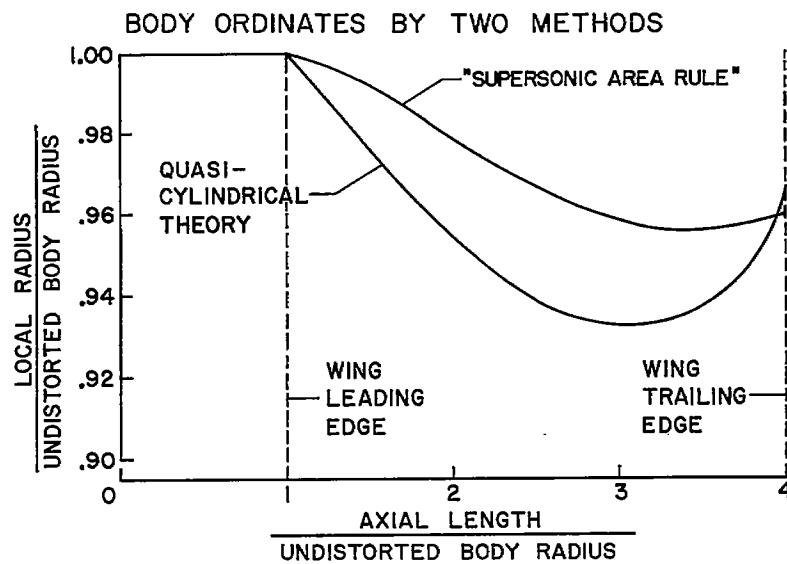

Figure 4

EFFECT OF MACH NUMBER

ASPECT RATIO = 2.66

— THEORY
o EXPER

Figure 5

BODY ORDINATES BY TWO METHODS
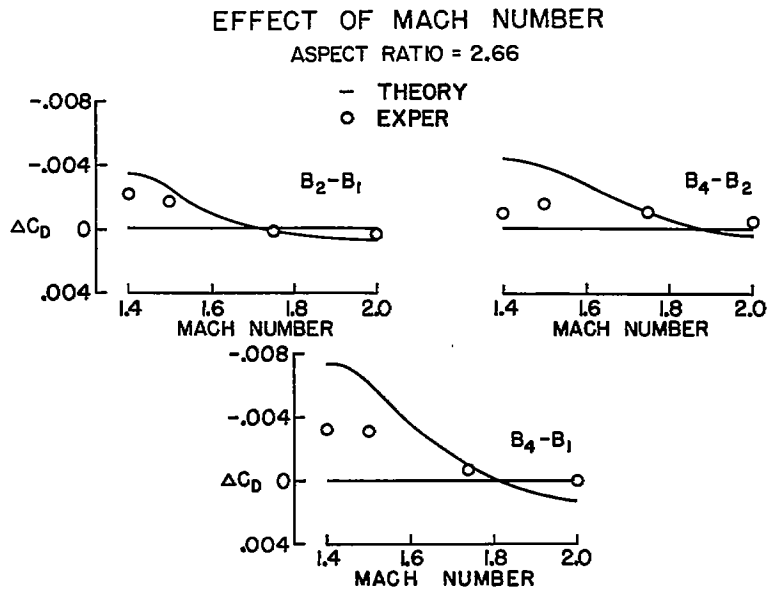
Figure 6

MODEL DESIGNED ACCORDING TO STREAM LINE CONTOUR
DESIGN MACH NUMBER = 1.02

SUBSONIC LEADING EDGE

AXISYMMETRIC BODY

STREAMLINE-CONTOURED BODY

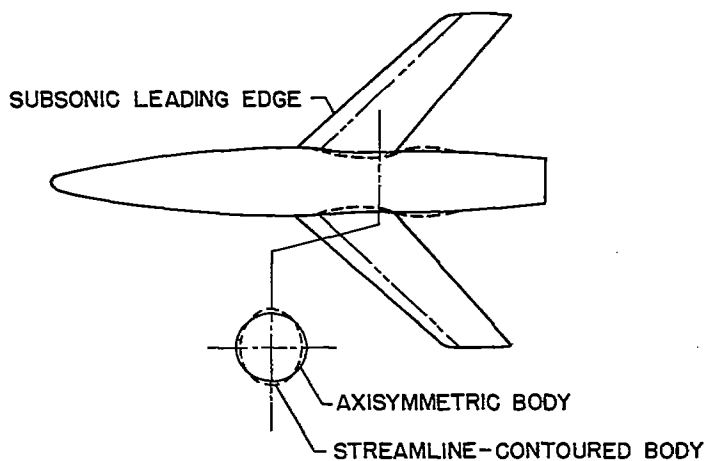Figure 7

DRAG SAVING BY STREAMLINE CONTOURING
DESIGN MACH NUMBER = 1.02

AXISYMMETRICAL INDENTATION
STREAMLINE-CONTOURED INDENTATION

Figure 8